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RESEARCH DIRECTED TOWARD THE USE OF LONG AND INTERMEDIATE PERIOD SEISMIC WAVES FOR THE IDENTIFICATION OF SEISMIC SOURCES

by

JOHN A. KELLEHER

Lamont-Doherty Geological Observatory

Columbia University
Palisades, New York 10964

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Work Unit No. 86520101

ANNUAL TECHNICAL REPORT NO. 2

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Terrestrial Sciences Laboratory

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
UNITED STATES AIR FORCE
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ABSTRACT

Seismological research supported by Air Force contract F19(628)-68-C-0341 at the Lamont-Doherty Geological Observatory is summarized for the period 1 August 1969 to 1 July 1970. During this period extensive analysis was done on the excitation of long-period (15-70 seconds) Rayleigh and Love waves by earthquakes, underground explosions and presumed explosions. The use of 40 second rather than 20 second surface wave amplitudes for m_b - M_s graphs was shown to have some distinct advantages for purposes of detection and discrimination. A complementary study of the nature and sources of long period earth noise (15-150 seconds) was completed. The continued operation of the network of intermediate and long-period instruments was essential to this research. Computational procedures for tracing seismic rays in a heterogeneous spherical earth were improved considerably. These improved methods led to important information on seismic velocity anomalies. Microearthquakes studies of Central and Southern Nevada gave insight concerning the tectonic strain release effected by a nuclear test shot. A region-by-region analysis of reliable focal mechanism solutions for deep and intermediate depth earthquakes provided additional support for the idea that portions of the lithosphere that descend into the mantle act as slab-like stress guides. A study of the space-time distribution of major earthquakes in the Alaska - Aleutian region suggests that these events do not occur randomly either in time or in space. Progress in each of these areas, particularly the analysis of long-period surface waves, has contributed materially to the capability to detect and identify seismic events.

INTRODUCTION

This report summarizes research carried on under the sponsorship of the Air Force Cambridge Research Laboratory and the Advanced Research Projects Agency through Contract F19(628)-68-C-0341 with the Lamont-Doherty Geological Observatory of Columbia University. In order to discuss this research in terms of the work statement of the contract, a copy of that statement is included in this report.

A list of publications supported by this contract during this period is attached to this report.

WORK STATEMENT

The work statement of contract F19(628)-C-0341 is as follows:

A. The contractor shall, unless otherwise indicated herein, supply the necessary personnel, facilities, services and materials to accomplish the following:

Line Item 1 - Operate and maintain the network of eight (8) widely distributed long- and intermediate-period stations formerly supported under contract AF19(628)-4082 to furnish data for seismological investigations related to the detection and identification of earthquakes and underground nuclear explosions. These stations by name and code are Palisades, N.Y. (PAL); Sterling Forest, N.Y. (SFO); Huancayo, Peru (HUA); Honolulu, Hawaii (HON); Mount Tsukaba, Japan (MTJ); Bokaro, India (BOK); Canberra, Australia (CAN); and one to be determined during the contract period. Changes in the numbers and locations of the stations are not to be made without prior written approval of the Contracting Officer. Investigations using data for these stations and other data sources (e.g. Montana and Norway LASA's, VELA-UNIFORM observatories, WWSSN, etc.) shall consist of but not be limited to the following:

Sub-Line Item 1AA - Extend the studies of the relative excitation of body and surface waves by earthquakes and underground explosions to small magnitude events. Determine discrimination thresholds both theoretically and empirically.

Sub-Line Item 1AB - Investigate the general characteristics of seismograms, such as the presence or absence of phases, dominant periods, duration, etc., as a function of source mechanism, region, focal depth and radiation pattern, and the relation of these features to the problems of detection and identification of seismic events. Emphasis should be placed on studies of the PL and compressional and shear coupled leaking modes, the depth phases, and multiples of P and S and on methods to selectively enhance these phases.

Sub-Line Item 1AC - Conduct detailed seismicity studies of geographic areas of interest to the VELA-UNIFORM Program.

Sub-Line Item 1AD - Investigate the LASA amplitude and traveltime anomalies.

Sub-Line Item 1AE - Develop seismic instrumentation to increase sensitivity in the long-period range and improve discrimination against noise in the dominant microseism band.

Sub-Line Item 1AF - Develop techniques for analyzing micro-seismic data and conduct studies of microseismic data.

Sub-Line Item 1AG - Investigate aspects of the New Global Tectonics that are of particular relevance to the problems of detection and identification of seismic events and to the problem of predicting optimum siting of seismic stations, networks and arrays.

Sub-Line Item 1AH - Conduct studies of near earthquakes and explosions to determine properties of the source, of the propagation path and of the crust and upper mantle in the vicinity of LASA arrays.

Sub-Line Item 1AJ - Conduct detailed studies of wave propagation, of source characteristics, and of surface and body waves of short and long periods originating at teleseismic distances with particular emphasis on regions with complicated crust and mantle structure.

MAJOR SCIENTIFIC ACCOMPLISHMENTS

In the following paragraphs, scientific accomplishments are summarized following the itemization in the statement of work of this contract. In accordance with the wishes of AFCRL and ARPA, emphasis has been placed on certain items and work on other items has been minimized or eliminated.

Item 1

Operation of the world-wide Lamont-Doherty network of long - and intermediate - period seismic stations, including the Padisades and Sterling Forest stations, continued during the present contract period. Stations under the support of this contract include the following:

Station Code	Station Name	Latitude	Longitude
PAL	Palisades, N.Y.	41 00 25.0N	73 54 31.0W
SFO	Sterling Forest, N.Y.	41 12 30.0N	74 15 00.0W
HUA	Huancayo, Peru	12 02 18.1S	75 19 22.1W
HON	Honolulu, Hawaii	21 19 18.0N	158 00 30.0W
MTJ	Mount Tsukaba, Japan	36 12 39.0N	140 06 36.0E
CAN	Canberra, Australia	35 19 15.0S	148 59 55.0E
RDJ	Rio de Janiero, Brazil	22 53 42.0S	43 13 24.0W
LWI	Lwiro, Congo	2 14 18.0S	28 48 00.0E

Item 1AA

a) Relative Excitation of Body and Surface Waves by Explosions and Earthquakes.

The excitation of long-period (15-70 sec) Rayleigh and Love waves by earthquakes, and underground explosions and presumed explosions was analyzed for four different regions of the world; western United States, the Aleutians, Novaya Zemlya, and Central Asia. A complementary study of the nature and sources of long-period earth noise (15-150 seconds) was completed. Papers describing these two studies are in preparation. Data for these investigations come from the systems operated in the deep mine at Ogdensburg, New Jersey. These investigations lead to the following conclusions:

1. The detection and discrimination of events in the western United States, the Aleutians, the Novaya Zemlya region, and central Asia is enhanced on the $M_s - m_b$ basis using 40 second rather than 20 second surface wave amplitudes. The separation of earthquakes and explosions into two populations is at least 25-50% more distinct at 40 seconds than at 20 seconds for most of the events studied. One event in particular, an explosion aftershock, plots very close to the explosion population on the basis of its $M_s - m_b$ data at 20 seconds. At 40 seconds, however, the separation between this event and the nearest observed explosion is a factor of 2 times greater.

2. The 40 second M_s -versus- m_b discriminant, unlike its 20 second counterpart can be applied to events in different regions (i.e., explosions in the western United States can be compared with earthquakes in the Aleutians for separation at 40 seconds).

3. A discriminant based on surface waves in the period range near 40 seconds is more reliable than one based on 20 seconds because of the existence of a relatively stable earth noise minimum, or window,

between 30-40 seconds. The maximum amplitude variation of this noise minimum over a period of one year has been observed to be only a factor of 3, resulting at most in a degradation of the 40 second detection threshold of only 0.2-0.3 m_b units. The 20 second background, however, undergoes amplitude variations of 1 to 2 orders of magnitude over short periods of time, which can degrade the 20 second detection threshold by as much as 1.0 m_b unit or more.

4. The 20 and 40 second surface wave detection threshold for earthquakes in the distance range 30° - 75° is approximately constant at a value of m_b = 4.4 (USCGS). This value also defines the event discrimination threshold over this distance range (i.e., an event occurring in the Aleutians, assigned an m_b (USCGS) of 4.4, would excite Rayleigh waves, observable at Ogdensburg, if it is an earthquake).

5. Rayleigh wave amplitude spectra in the period range 20-55 seconds fall off faster at the longer periods for a presumed underground explosion than for earthquakes in the Novaya Zemlya region. For example, mean values of the 20/40 second amplitude ratio are; explosion: 5.4, earthquakes: 1.6. Thus, the 20/40 second Rayleigh wave amplitude ratio provides for an additional new discriminant between earthquakes and explosions in this region.

6. Rayleigh wave amplitude spectra for Aleutian earthquakes scatter considerably and in some cases exhibit a faster long period fall off than observed for the underground explosion, Milrow. The observed scatter is attributed to variations in focal depths. Thus the simple 20/40 second ratio test, which discriminates between events in the Novaya Zemlya region, does not work for all events in the Aleutians.

7. Differences in the shape of the 20-50 second portion of the Fourier amplitude spectra between a shallow explosion aftershock ($h \approx 3.5$ km) and 3 NTS explosions imply that differences in source time functions for earthquakes and explosions are mainly responsible for the success of the 20/40 second ratio discriminant. The shapes of the Fourier amplitude spectra for a Jorum (explosion) cavity collapse and 3 NTS explosions are nearly identical between 20 and 50 seconds. However, due to the wide-band response of the high-gain instruments, shorter period (15-18 seconds) differences in the spectra allow for discrimination between these two types of events. This collapse also separates from the explosion population on the $M_s - m_b$ basis at 20 and 40 seconds.

8. The 20/40 second ratio for the underground explosion, Rulison, which occurred in Rifle, Colorado, is similar to that observed for western United States earthquakes. Spectral differences between Rulison and NTS explosions are attributed to differences in the shot-point media and/or propagation paths. However, Rulison falls in with the NTS explosions on the $M_s - m_b$ plot at 20 and 40 seconds.

9. Differences in the 20/40 second Rayleigh wave amplitude ratio for different regions, in particular the value of this ratio for Rulison, indicate a strong regional dependence. Thus it is important that this ratio test is only applied to events from the same region.

10. The detection of Love waves, in the absense of observable Rayleigh waves, demonstrates the importance (on a detection basis) of the successful operation of high-gain horizontals as well as vertical instruments.

11. Body wave magnitude for earthquakes and explosions studied by Molnar et al. (1969) as well as for some additional events in the western United States have been redetermined using Evernden's formulas for the · stern United States. Data was obtained from short period records of WWSSN station and from published data in the EDR reports. Plots of both the 40 second and 20 second Rayleigh wave vs. the revised body wave magnitude (m_b), exhibit clearer separation of the earthquakes from the explosions than w s found by Molnar et al. using CGS data. This is especially clear from the 40 second surface waves, implying that for discrimination a surface wave magnitude scale based on 40 second waves is more reliable than one using 20 second waves.

b) Aftershocks from the JORUM Underground Nuclear Explosion.

A team of seismologists operated six microearthquake seismographs in an area 150-200 km due north of the nuclear test site before and after the nuclear test, Jorum. The purpose of their study was to investigate whether nuclear underground explosions might affect the seismicity as far as 100 to 200 km from the test site.

The preliminary result, reported at the western meeting of the A.G.U. in December, 1969, is that there was no increase in seismic activity in the immediate vicinity of the instruments and that the number of aftershocks from near the shot-point recorded at a distance of 175 km was down by a factor of approximately 100 from the number similarly recorded after the explosion Benham.

Work is continuing on the location of events local to the instruments.

c) Source Dimensions of Small Earthquakes

Data derived from studies by other workers of prominent, well-defined aftershock sequences are employed to obtain evidence for the source dimensions of earthquakes in the magnitude range m = 4 1/2 to 6. The characteristic length of the aftershock zone is defined as the longest dimension of the map view of the aftershock epicenters. On the basis of this aftershock data, the following rough limits may be placed on the likely size of small earthquakes in the western United States; for magnitude 5 events, 50 to 25 km; for magnitude 4 events, 2 to 15 km. These limits are about an order of magnitude larger than those proposed by Press for earthquakes and underground explosions and represent an independent confirmation of the results for earthquakes of Wyss and Brune. The larger dimensions suggest that differences in the seismic spectra of earthquakes and underground explosions should persist even for some events as small as m = 4. These results have an important bearing on recent studies of the excitation of surface waves by earthquakes and underground explosions. A paper reporting these results has been published: Liebermann, R. C., and P. Pomeroy, Source Dimensions of Small Earthquakes as Determined from the Size of the Aftershock Zone, Bull. Seism. Soc. Am., 60, 879, 1970.

Item 1AB

a) A revised manuscript "Oceanic Long-Period S Waves" was prepared for publication. It summarizes the observations of waves with 20 to 40 sec period following the S-phase at epicentral distances 50° and 85° along purely oceanic paths.

An attempt was made to devise a method of synthesizing shear-coupled PL waves that is simpler than the method proposed by Chander et al. (1968). The method reduces the number of steps involved in a synthesis drastically (factor of 4 or better) and makes it even suitable for a desk calculator. The basis for synthesis is still the shear-coupled PL wave hypothesis; but, in the numerical evaluation of the relevant integral, the summation of Chander et al.'s method is replaced by a single term. The results from the two methods are essentially the same. The usefulness of synthesis in determining leaking mode dispersion curves or testing body-wave travel times is retained.

b) A paper entitled "Leaky Modes - a Plane Wave Approach" has been submitted to the Bulletin of the Seismological Society of America. The paper demonstrates that the ray model for leaky modes proposed by Burg et al. yields the usual period equation for leaky modes. The ray model is shown to yield an inhomogeneous wave and the physical structure of the leaky mode can be better understood. Since the mode is generated by long-period compressional and shear waves, the possibility exists of using spectra from direct and shear-coupled PL modes for identification criteria.

c) Seismic Ray Tracing.

The computational procedures for tracing seismic rays in a heterogeneous spherical earth have been improved. The improved method was applied to determine the magnitude and shape of major heterogeneities in seismic velocities in the upper mantle in the Tonga and the Aleutian island arcs.

The results show that the lithosphere dipping beneath the Tonga arc to a depth of about 700 km is about 6 to 7% faster for P waves than the regular mantle. The seismic velocities in the dipping lithospheric slab in depths between 50 and 200 km may vary by as much as +10% from normal mantle velocities. Similar results are obtained for the Aleutians from a comparison of Longshot travel times with those calculated by the ray tracing program. The "source bias" of P travel times for the nuclear explosion Longshot was determined as a function of distance and azimuth.

Also a new P residual map for the United States has been derived from the same Longshot data. Both the source residuals and the station residuals may be subject to slight changes since very recent data indicate that the seismic active zone, and thus the lithosphere, are at a shallow depth beneath the Amchitka island than the depth used in the present models.

The basic principles of the developed method of ray tracing and their implications for precise relocation of nuclear underground explosions and earthquakes as well as for measuring $dT/d\Delta$ with large seismic arrays has been summarized in a paper submitted for publication.

Item 1AC

a) Microseismicity of Southwest Nevada.

A field party that went to the southwest section of Nevada operated six portable, high-frequency, high-gain instruments from December, 1968 to February, 1969. During the last year the data collected from this region have been analyzed at Lamont-Doherty. The epicenters were determined for 300 microearthquakes and their local magnitudes calculated using the technique of Brune and Allen (1967). First motions of the P wave were noted for several of the better located events. Through the use of the composite focal mechanism technique these first motions were combined to determine focal mechanisms. Two focal mechanisms were determined; one for earthquakes along Excelsior Mountain showed left-lateral strike-slip motion and another for Cedar Mountain exhibited normal faulting. The focal mechanisms and the earthquake epicenters were combined to infer the regional trend of tectonics. The results were presented in a talk at the April, 1970 meeting of the American

Geophysical Union in Washington, D.C.

b) ESSA, USCGS, Epicenter Data, 1961-1969.

A short note entitled "Seismicity map of the Arctic compiled from ESSA, Coast and Geodetic Survey, epicenter Data, January, 1961-September, 1969" has been prepared and sent to the Bulletin of the Seismological Society of America for publication. This note presents a seismicity map of the Arctic region north of latitude 70°N containing epicenters of 310 earthquakes compiled by ESSA, USCGS, for the interval Jan. 1, 1961 through Sept. 30, 1969. All of the hypocenters are shallow, i.e., depth less than 100 km. The most significant feature of the seismicity map is the seismic belt between northeast Greenland and northern Siberia. It defines a very straight trend for about 20°, and is perhaps the longest active linear feature of the mid-ocean ridge system. This belt extends into the Eurasian continent in Siberia but the epicenters there are few and scattered.

Item 1AD

No further work has been done on this item.

Item 1AE

Untra High-Gain, Long Period Instrumentation.

An eight channel digital recording system (on loan from the Geo-acoustics Division of ESSA) was added to the high-gain seismograph system at Ogdensburg, New Jersey. Computer programs for plotting the data, performing power spectral and Fourier analysis of this data were written. High resolution, high confidence (88 degrees of freedom) power spectra of long period earth noise were computed for different days. These latest results confirm earlier power spectral results with more limited dynamic range, and allow for study of fine structure in the power spectra. These results are included in the paper on long-period earth noise (item 1AAa).

Item 1AF

The problem of the sources of the various components of the earth noise has been addressed, using data from LASA, and, to a large extent, solved. A paper describing this work has been published: Haubrich, R. A., and K. McCamy, Microseisms: Coast and Pelagic Sources, Reviews of Geophysics, 7, 539-571, 1969.

Item 1AG

a) Distribution of Stresses in the Descending Lithosphere from a Global Survey of Focal Mechanism Solutions of Earthquakes in the Mantle.

A region-by-region analysis of 204 reliable focal mechanism solutions for deep and intermidiate-depth earthquakes strongly supports the idea that portions of the lithosphere that descend into the mantle act as slab-like stress guides which align the earthquake-generating stresses parallel to the Benioff zone. At intermediate depths extensional stresses parallel to the dip of the zone are predominant in zones characterized either by gaps in the seismicity as a function of depth or by an absense of deep earthquakes. Compressional stresses parallel to the dip of the zone are prevalent everywhere below about 300 km. These results indicate that the lithosphere can sink into the asthenosphere under its own weight but encounters resistance to its downward motion below about 300 km. The results also indicate contortions and disruptions of the descending slabs; however, stresses attributable to simple bending of the plate do not seem to be important in the generation of subcrustal earthquakes. Data are included for nearly every region in the world where earthquakes occur in the mantle.

b) A paper entitled "Tectonics of the Caribbean and Middle America Regions from Focal Mechanisms and Seismicity" by Peter Molnar and Lynn Sykes has been published in the Bulletin of the Geological Society of America, September 1969. This paper discussed the tectonics of the region and demonstrates the consistency of recent ideas of global tectonics for relatively small plates.

c) A study of space-time patterns in the distribution of major earthquakes of the Alaska - Aleutian seismic zone indicates that major earthquakes of this zone tend to progress in time from east to west. Extrapolation of past trends indicates that a major Alaska - Aleutian earthquake will probably occur near 56N, 158W between about 1974 and 1980.

Three kinds of evidence indicate that earthquakes of about magnitude 7.7 and larger should be used to identify space-time earthquake patterns in the Alaska - Aleutian seismic zones: (1) Space-time graphs of earthquakes of about magnitude 7.7 and larger show strong linear trends; (2) Aftershock zones of successive large earthquakes ($M \geq 7.7$) are approximately adjacent; (3) The direction of fracture propagation is generally away from the focal zone of the previous adjacent large earthquake. This suggests that the concentration of stress prior to the event was greatest near the region of the adjacent earlier earthquake. Since this pattern is reasonably consistent, the linear trends of large earthquakes in this seismic zone are probably due to some physical phenomena rather than some unusual chance distribution.

The space-time distribution of the USCGS epicenters for 1961-1967 suggest that these past trends will continue. These epicenters show a distinct seismicity gap in the region predicted for a major Alaska - Aleutian earthquake. In the past, such gaps have often occurred before major earthquakes.

A paper reporting these results has been submitted to the Journal of Geophysical Research.

d) Twenty focal mechanisms for shallow earthquakes in the Solomon Islands - New Hebrides region have been completed. These mechanisms combined with others currently being studied will give a clearer understanding of the present tectonics of this region and the South Pacific in general.

e) A paper entitled "Seismicity and Tectonics of the Western Pacific: Izu-Mariana-Caroline and Ryukyu-Taiwan Regions" by Mamoru Katsumata and Lynn R. Sykes has been published in the Journal of Geophysical Research. This paper discusses the results of relocating the hypocenters of about 1000 earthquakes; in addition, earthquake mechanism solutions based on the first motions of P, pP, and S were determined for 26 earthquakes. The spatial distributions and focal mechanisms of these earthquakes are compared with major tectonic features, such as volcanic zones, island arcs, and trenches in the studied regions.

f) Focal Mechanisms

Three papers based on a collection of focal mechanism solutions from recent earthquakes in the seismic zones between the Hindu Kush and the Philippines give additional support to plate theory and new global tectonics (Focal mechanisms along inclined seismic zones in the Indonesian-Philippine region, Fitch and Molnar; Focal mechanisms and island arc tectonics in the Indonesian-Philippine region, Fitch; Earthquake mechanisms in the Himalayan, Burmese and Andaman regions and continental tectonics in Central Asia, Fitch). These investigations, in addition to numerous other studies of focal mechanisms based on modern data, suggest that earthquakes in a given region nearly always have the same mechanism solution, e.g., on the convex side of most active island arcs there is a zone of underthrusting in which nearly all earthquakes yield an underthrusting type mechanism. In the near future these studies will allow one to predict in a general way with great certainty the mechanism for an earthquake when given its location.

Item 1AH

No further work has been done on this project.

Item 1AJ

Two computer programs for calculating the propagation of Love and Rayleigh waves respectively in two dimensional heterogeneous media have been written. The programs solve the two dimensional elastic wave equation by finite differences. Initial comparisons of the obtained solution with models used previously by Alsop, and McGarr and Alsop yield satisfactory agreement. Since surface wave amplitudes are used for discrimination, it is possible to use this technique to study possible mechanisms for the reduction of surface wave amplitudes.

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Wholly or in part by Contract F19(628)-C-0341

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LIST OF PERSONNEL

Scientists:

L. E. Alsop	M. Katsumata	J. Nafe
H. J. Dorman	J. Kuo	A. Nowroozi
M. Ewing	G. Latham	J. Oliver
B. Isacks	K. McCamy	R. Page
K. H. Jacob	T. Matumoto	C. Scholz
K. Hamada		L. Sykes

Graduate Students:

M. Barazangi	M. Fliegel	P. Molnar
R. Chander	F. Gumper	A. Murphy
K. Farrell	T. Johnson	J. Rynn
T. Fitch	J. Kelleher	J. M. Savino
J. Fletcher	J. Lahr	M. Sbar
	W. Mitronovas	

Engineers:

M. Connor

F. England

G. Hade

F. G. van der Hoeven

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13. ABSTRACT

Seismological research supported by Air Force contract F19(628)-C-0341 at the Lamont-Doherty Geological Observatory is summarized for the period 1 August 1969 to 1 July 1970. During this period extensive analysis was done on the excitation of long-period (15-70 second) Rayleigh and Love waves by earthquakes, underground explosions and presumed explosions. The use of 40 second rather than 20 second surface wave amplitudes for m_b-M_s graphs was shown to have some distinct advantages for purposes of detection and discrimination. A complementary study of the nature and sources of long period earth noise (15-150 second) was completed. The continued operation of the network of intermediate and long period instruments was essential to this research. Computational procedures for tracing seismic rays in a heterogeneous spherical earth were improved considerably. These improved methods led to important information on seismic velocity anomalies. Microearthquakes studies of Central and Southern Nevada gave insight concerning the tectonic strain release effected by a nuclear test shot. A region-by-region analysis of reliable focal mechanism solutions for deep and intermediate depth earthquakes provided additional support for the idea that portions of the lithosphere that descend into the mantle act as slab-like stress guides. A study of the space-time distribution of major earthquakes in the Alaska-Aleutian region suggests that these events do not occur randomly either in time or in space. Progress in each of these areas, particularly the analysis of long-period surface waves, has contributed materially to the capability to detect and identify seismic events.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Seismicity						
Elastic wave calculations on digital computer						
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